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SIMULATION OF A COMBINED-CYCLE ENGINE

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### Abstract

A FORTRAN computer program has been developed to simulate the performance of combined-cycle engines. These engines combine features of both gas turbine and reciprocating engines. The computer program described and documented in this report can simulate both design point and off-design operation. Widely varying engine configurations can be evaluated for their power, performance and efficiency as well as the influence of altitude and air speed. Although the program was developed to simulate aircraft engines, it can be used with equal success for stationary and automotive applications.

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# SIMULATION OF A COMBINED-CYCLE ENGINE

## 1 Introduction

As part of a project to develop a high-efficiency engine for use in helicopters, the U.S. Army Aviation Systems Command authorized the development of a simulation capability for estimating the off-design performance of combined-cycle engines. These are engines that have features of both gas turbine and reciprocating engines. This document is the final report for the project to develop this simulation capability.

During a Summer Faculty Fellowship in 1988, the author developed a computer program for simulating two-stroke diesel engines. This program was documented in reference [1]. While this program allowed prediction of diesel engine performance it required knowledge of the intake air supply pressure and temperature as well as the exhaust back pressure. This information can be specified at a design point operating condition but at an off-design condition, it is usually unknown. In order to predict off-design performance, it is necessary to incorporate the characteristics of the compressors and turbines used to supply the air to the engine.

The Navy-NASA Engine Program (NNEPEQ) is an existing computer program that allows the off-design behavior of turbomachinery to be predicted and also solves the resulting matching problem [2,3]. The principle objective of the project described in this report was to combine the two-stroke diesel engine simulation program with NNEPEQ to obtain a combined-cycle engine simulation program.

This report is suitable as a user's manual for the combined-cycle engine simulation program. Since the two programs that comprise the simulation are documented elsewhere, details of these programs will not be provided. Only those features of the combined program that are new, or not discussed elsewhere, will be documented here.

The proposal for this project stated that in addition to the integration of the two simulation programs, other improvements would be made. These include upgrading the air scavenging model in the diesel program, investigating alternative compressor maps in NNEPEQ, incorporating second law analysis into the diesel program and allowing the use of crankshaft offset with opposed piston engines. While all of these features are addressed in this report, only the improved scavenging model has been incorporated into the combined cycle program. The other features are provided in special purpose programs. This requirement came about because of the need to dramatically reduce the execution time of the diesel simulation program. The version of the program described in reference [1] requires about 2-8 minutes of CPU time on a VAX 11/785. Since NNEPEQ will execute this program approximately 100 times for each operating condition and a typical run of NNEPEQ involves one design point run and 8-12 off-design point conditions, it is obvious that CPU times had to be reduced. Program modifications were made that reduced the execution time by a factor of 20 with only minimal changes in output. The combined program is currently being run on a DEC 3100 workstation and requires about 3 minutes for each operating condition.

This report will describe the improvements made to the diesel simulation, especially the air scavenging model. Then the features of the combined program

will be presented as well as the input and output from the program. These features will be illustrated with two sample cases. Following the sections on the combined-cycle engine simulation program, the other aspects of the contract work statement will be discussed. An appendix is provided describing a computer program for doing second law calculations. Another appendix shows how experimental data for a small centrifugal compressor was entered into the program and compared with the standard maps used by the program. Finally, the last appendix contains a subroutine for calculating diesel engine cylinder volumes for opposed piston engines with crankshaft phase offset.

## 2 Structure of the Combined-Cycle Simulation Computer Program

Figure 2.1 shows a schematic of the combined-cycle engine simulation computer program. The main program, called CCE, is very similar to the main program in NNEPEQ described in references [2,3]. However, it contains the call to a subroutine INPUT1 that reads the file containing the specifications of the diesel engine. The block of subroutines identified as NNEPLIB includes all the subroutines originally associated with NNEPEQ. Only a few have been modified to allow the simulation of a combined-cycle engine. CCE can still be run as a gas turbine simulation program and retains all the features of NNEPEQ.

The diesel portion of the simulation has been incorporated into the gas turbine simulation as a burner. The subroutine DBURNR from NNEPEQ was modified so that if a certain parameter is non-zero, the program flow branches out of DBURNR and calls the DIESEL subroutine.

There is a mis-match between the requirements of the turbomachinery portion of CCE and the diesel program. CCE provides each of the elements of the gas turbine engine with an incoming pressure, temperature and mass flow rate. It then calculates an exit pressure that corresponds to these conditions. However, the diesel program expects to receive an incoming pressure and temperature and an exit pressure. It then calculates the mass flow rate for these conditions. Due to this problem it was necessary to develop an interface subroutine that matches the information supplied by CCE to that required by the diesel program. This interfacing subroutine is called DIESEL and it calls the diesel simulation program DSL2 with estimated values of exhaust back pressure. It iteratively varies this pressure until the mass flow rate through the diesel matches that required by CCE.

The block of subroutines identified as ELIB includes the subroutines required by DSL2. These subroutines are separate from and do not depend on those present in NNEPLIB.

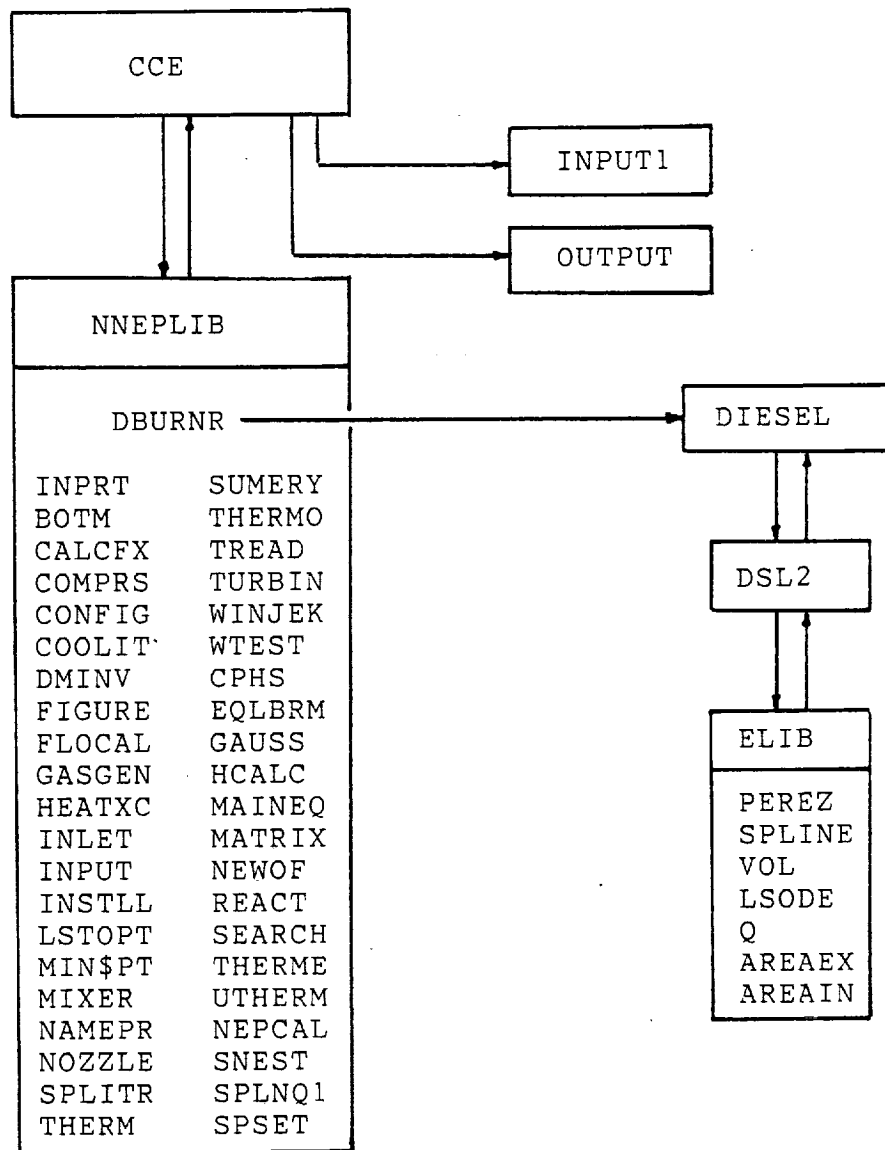


Figure 2.1 Structure of the Combined-Cycle Engine (CCE) Simulation Program

### 3 Modifications to the Diesel Simulation Program

#### 3.1 Air Scavenging Models

The original version of the diesel simulation computer program described in reference [1], has a very basic scavenging model that is not flexible enough to accommodate differences in the scavenging characteristics of various engines. One of the objectives of this project was to implement a more sophisticated scavenging model that would provide more accurate predictions of air flow requirements in two-stroke engines.

Three simple models for scavenging can be developed from the limiting cases corresponding to phenomena in two-stroke engines. One case, called "perfect scavenging," assumes the incoming air is separated from the exhaust gases by a membrane that prevents mixing. The incoming air pushes the exhaust out ahead of it and when enough air has been added to fill the cylinder, the exhaust gases have been completely expelled. Obviously, this is an ideal case and is never accomplished in a real engine.

The second limiting case is "perfect mixing." In this case, the incoming air is assumed to mix instantaneously with the product gases in the cylinder as it enters the cylinder. When the exhaust process begins most of the expelled gases are combustion products but as the process continues, an increasing fraction is fresh charge.

The final case corresponds to complete "short circuiting." This means that the air entering through the intake ports passes directly to the exhaust ports without expelling any exhaust products with it. This would be a highly undesirable form of scavenging since no fresh charge is retained for the next engine cycle.

The original engine simulation program uses a scavenging model that assumes perfect mixing. While this model will accurately predict power and efficiency in diesel engines, it underpredicts the air flow requirements of the engine. Most two-stroke engines produced today have scavenging characteristics somewhere between perfect mixing and perfect scavenging. A scavenging model that takes advantage of this fact is the "mixing-displacement scavenging" model developed by Benson and Brandham [4]. The details of the model are described below.

#### 3.2 Mixing-Displacement Scavenging Model

This model assumes that the cylinder is divided into two zones. One zone is called the mixing zone and the other the displacement zone. The ratio of the initial volume of the displacement zone to the total cylinder volume is called the displacement factor. At the point where both the intake and exhaust ports are open simultaneously, the start of the scavenging period, the exhaust gases leave the cylinder from the displacement zone following the commonly used rule based on isentropic flow of ideal gases through a reduced area section due to a pressure difference. Non-ideal behavior is incorporated with a discharge coefficient. Incoming air flows through the intake port following a similar relationship and enters the mixing zone where it is assumed to mix perfectly with the contents of that zone. The scavenging process continues until the contents of the displacement zone are completely exhausted and the mixing zone completely fills the cylinder. At this point, the products



leaving the cylinder are drawn from the mixing zone until the exhaust port closes. This model is a combination of a perfect mixing and perfect scavenging model. The displacement factor determines the relative weighting between the two models. This factor is chosen to provide scavenging characteristics that match experimental data, if available. The program currently uses a value of 0.55 for the displacement factor as this gives results typical of current production engines.

The diesel simulation program uses a single zone combustion model. This model is used up to the point where the intake port opens and then the single zone is split into the two zones described above. Under almost all conditions, the model reverts to a single zone model during the scavenging process because the displacement zone is entirely exhausted. It is conceivable that under very high speed conditions or when the pressure drop across the engine is very low, the displacement zone might not be entirely exhausted before the exhaust port closes. In this case, the two zones are instantaneously mixed at the point of exhaust port closure and the calculation continues with the single zone model.

Use of the mixing-displacement scavenging model requires no input from the user. It is automatically used when the program is used to simulate a two-stroke engine.

### 3.3 Change in Gas Property Routine

The diesel simulation routine described in reference [1] assumes that the contents of the engine cylinder are equilibrium combustion products at all times. The computer program used a subroutine, PERX, that was based on the subroutine PER developed by Olikara and Borman [5]. However, in a time study of the diesel simulation it was determined that the program was spending about 80% of its time calculating properties. To reduce the amount of time spent in property evaluation a new property routine was developed that assumes the products consist of oxygen, nitrogen, carbon dioxide and water vapor under lean conditions and nitrogen, carbon dioxide, carbon monoxide, hydrogen and water vapor under rich conditions. This change in property routine resulted in a reduction in CPU time from 465 seconds to 86 seconds on a VAX 11/785.

### 3.4 Change in Differential Equation Integrator

The final modification to the program was to change the differential equation integrator used to solve the time-based equations for pressure, temperature, etc. in the cylinder. The original version of the program used DVERK, a subroutine from the commercial International Mathematical Subroutine Library (IMSL). This program uses the Runge-Kutta numerical procedure which is highly accurate but not very efficient. This subroutine also has the disadvantage that the program can only be run on a computer that is licensed to use the IMSL programs. To eliminate these problems, the subroutine LSODE was substituted for DVERK. This subroutine is publicly available so it can be easily transported to other computers. In addition, it uses an implicit numerical procedure that is very efficient [6]. CPU time was reduced from 86 s 11 seconds using this routine. Accuracy was such that no significant difference could be detected between results obtained with this routine and those derived using the IMSL program.

#### 4 Inputs to the Combined Cycle Engine Simulation Program

Input to the combined-cycle engine simulation program is provided by two data sets. The first data set corresponds very closely to the NAMELIST data input file used by NNEPEQ and completely characterizes the turbomachinery associated with the engine. The only modifications to this file are that if a diesel engine is included in the engine design, the engine fueling rate and speed are input through this data set. A conventional gas turbine engine data set can be provided to the program and it will run normally and provide the same results as NNEPEQ.

The second input data set provides the specifications of the diesel engine. This data set is a slightly modified version of the data set used by the original two-stroke diesel engine program [1].

The turbomachinery data set is read from a file named "TURBO.INP." The diesel data set is read from a file named "DSL.INP". A third data file contains the turbomachinery maps. A default set of maps is provided with NNEPEQ and they were used for the example cases described later. The map file is read from logical unit 12. This means that an ASSIGNMENT statement must be used to identify the actual data file name as unit 12.

The turbomachinery input data file is relatively complex and provides a great deal of flexibility in specifying engine configuration and component specifications. Since it is essentially identical to the input data file used by NNEPEQ, and is well-documented elsewhere [2,3], only the general features of the input file will be presented here. This report assumes the reader has a working knowledge of the NNEPEQ program.

The first line in the turbomachinery NAMELIST is a title for the cases and can be up to 60 characters in length. Following this line is the NAMELIST data. The following is an abbreviated list of variable definitions. The NNEPEQ manual should be consulted for the complete list.

NCOMP = The total number of components including controls that will be configured.  
TABLES = TRUE if maps are used, FALSE if not. (Default is TRUE)  
PUNT = Set PUNT = TRUE to use last good point as set of first guesses for next point. It is advisable to always have PUNT = TRUE. (Default is TRUE)  
LONG = Control for printing a history of the convergence process. It is advisable to have LONG = TRUE for new problems. (Default is TRUE)

The first NAMELIST read process inputs these variables and then, if TABLES = TRUE, the code will read in the maps. Now the program is ready to read in the engine configuration data.

Each type of component has a different set of input variables. However, the form of the input is the same for all components. For all components except controls the input data is read in the following form.

```
KONFIG(1,N)=M,JM1,JM2,JP1,JP2,  
SPEC(1,N)=V1,V2,...,V15
```

where N is the component number

M is a number corresponding to the type of component where

- 1 = inlet
- 2 = duct or burner
- 3 = gas generator
- 4 = compressor
- 5 = turbine
- 6 = heat exchanger
- 7 = splitter
- 8 = mixer
- 9 = nozzle
- 10 = load
- 11 = shaft
- 12 = control

JM1 is the primary upstream airflow station number for flow components or the first component hooked onto a shaft

JM2 is the secondary upstream station number, or the second component hooked onto a shaft

JP1 is the primary downstream station number, or the third component hooked onto a shaft

JP2 is the secondary downstream station number, or the fourth component hooked onto a shaft

The SPEC array is used to define the characteristics of the component identified in the KONFIG statement. The SPEC statement could specify as many as 15 different parameters but most components do not use all 15. Table 4.1 is extracted from reference [3] and defines the values of the SPEC array for each component.

---

Table 4.1 Definitions of the Configuration Variables

Device Type 1: Inlet

SPEC(1,N)=Inlet weight flow, lb/sec  
SPEC(2,N)=Free stream temperature, R  
SPEC(3,N)=Free stream pressure, psia  
SPEC(4,N)=Inlet drag table reference number, if blank computed  
SPEC(5,N)=Mach number at inlet  
SPEC(6,N)=Inlet recovery factor, constant or table reference number  
If =0, Mil spec is used  
SPEC(7,N)=Maximum permitted flow if table specified in SPEC(6,N)  
SPEC(8,N)=Scale factor on flow if table specified in SPEC(6,N)  
SPEC(9,N)=Altitude, feet, used only if SPEC(2,N), SPEC(3,N) =0  
SPEC(10,N)=Fuel/air ratio at inlet, usually =0  
SPEC(11,N)=If nonzero, SPEC(9,N) is geopotential altitude  
SPEC(12,N)=Temperature change to be added to SPEC(2,N), usually zero  
SPEC(13,N)=Blank  
SPEC(14,N)=Corrected flow at inlet entrance (if specified, will override SPEC(1,N))  
SPEC(15,N)=Corrected flow at inlet exit (if specified, will override SPEC(1,N))

Device Type 2: Duct (or Diesel Engine)

SPEC(1,N)=Pressure drop/inlet pressure or table reference number  
SPEC(2,N)=Optional, design duct Mach number

SPEC(3,N)=0 for duct, if nonzero then program assumes this device  
 is a diesel engine and this is the mass of fuel injected per  
 cylinder per cycle  
 SPEC(4,N)=If SPEC(3,N)=0, then burner outlet temperature if positive  
 simple duct if zero  
 fuel/oxidizer ratio if negative  
 If SPEC(3,N).GT.0, then equal to diesel engine speed  
 SPEC(5,N)=Burner efficiency or table reference number  
 SPEC(6,N)=Fuel heating value or table reference number  
 SPEC(7,N)=Cross sectional area of duct or burner, sq inches  
 SPEC(8,N)=Ratio of inlet entrance bleed flow to total bleed available  
 SPEC(9,N)=Exit bleed/total flow  
 SPEC(10,N)=Fraction of air not heated

#### Device Type 3: Gas Generator

SPEC(1,N)=Output temperature, R  
 SPEC(2,N)=Fuel/oxidant weight ratio  
 SPEC(3,N)=Generator pressure, psia  
 SPEC(4,N)=Fuel flow rate, lb/sec  
 SPEC(5,N)=Oxidant flow rate, lb/sec

Not all of these SPEC's can be specified simultaneously. The options are

1. SPEC(1) and SPEC(4)
2. SPEC(1) and SPEC(5)
3. SPEC(2) and SPEC(4)
4. SPEC(2) and SPEC(5)
5. SPEC(4) and SPEC(5)

#### Device Type 4: Compressor

SPEC(1,N)=R value used to read tables  
 SPEC(2,N)=Compressor bleed flow/total flow  
 SPEC(3,N)=Scale factor for corrected speed  
 SPEC(4,N)=Table reference number for corrected speed  
 SPEC(5,N)=Scale factor for corrected flow  
 SPEC(6,N)=Table reference number for corrected flow  
 SPEC(7,N)=Scale factor for efficiency  
 SPEC(8,N)=Table reference number for efficiency  
 SPEC(9,N)=Scale factor on input pressure ratio, SPEC(13,N)  
 SPEC(10,N)=Third dimension argument value on map (variable geometry)  
 SPEC(11,N)=Fractional bleed horsepower loss due to interstage bleed  
 =0 means all bleed after full compression  
 SPEC(12,N)=Desired adiabatic efficiency at design point  
 SPEC(13,N)=Desired pressure ratio at design point R value and  
 corrected speed  
 SPEC(14,N)=Corrected speed for design point on maps

#### Device Type 5: Turbine

SPEC(1,N)=Pressure ratio at design point on maps  
 SPEC(2,N)=Total bleed in/Total bleed available  
 SPEC(3,N)=Scale factor for corrected speed, usually 1  
 SPEC(4,N)=Table reference number for corrected flow  
 SPEC(5,N)=Scale factor for corrected flow  
 SPEC(6,N)=Table reference number for turbine adiabatic efficiency  
 SPEC(7,N)=Scale factor to get design point efficiency at design  
 point on map  
 SPEC(8,N)=Scale factor calculated to get desired pressure ratio

on map  
 SPEC(9,N)=Turbine bleed flow at entrance/bleed flow  
 SPEC(10,N)=Third dimension argument value on map  
 SPEC(11,N)=Desired efficiency at design point  
 SPEC(12,N)=Corrected speed at design point on map  
 SPEC(13,N)=Turbine horsepower split (usually =1)

Device Type 6: Heat Exchanger

SPEC(1,N)=Pressure Drop/Inlet pressure for main flow  
 SPEC(2,N)=Pressure drop/Inlet pressure for secondary flow  
 SPEC(3,N)=Temperature rise for main flow (main flow must be heated)  
 SPEC(4,N)=Effectiveness  
 SPEC(5,N)=Scale factor on effectiveness

Device Type 7: Splitter

SPEC(1,N)=Bypass ratio (Bypass flow/main flow)  
 SPEC(2,N)=Pressure drop/inlet pressure for main stream  
 SPEC(3,N)=Pressure drop/inlet pressure for bypass stream

Device Type 8: Mixer

SPEC(1,N)=Inlet area of main flow calculated at design point  
 SPEC(2,N)=Inlet area of secondary flow calculated at design point,  
     if SPEC(7,N)=2, then throat area  
 SPEC(3,N)=Total to static pressure ratio at main flow inlet if greater  
     than 1, if less than 1 = Mach number at design point  
 SPEC(4,N)=velocity coefficient on mixed flow velocity, if SPEC(7,N)=2  
     then momentum coefficient for ejector primary (1=ideal, less  
     than 1=less than ideal)  
 SPEC(5,N)=If =1 total inlet area is held fixed as second area varies,  
     if =0, independent areas  
 SPEC(6,N)=This parameter can have a value of 0 or 1. If =0 the definition  
     of SPEC(3,N) is as described above. If =1 then SPEC(3,N) is the  
     minimum total to static pressure ratio or the minimum Mach  
     number of either stream  
 SPEC(7,N)=If =0 then normal mixer, =1 supersonic mixer, =2 ejector  
     To use SPEC(7,N)=2, the user should consult the NNEPEQ manual  
     for additional input requirements

Device Type 9: Nozzle

SPEC(1,N)=Flow area, sq inches, exit for converging, throat for C-D  
 SPEC(2,N)=Flow coefficient or table reference number  
 SPEC(3,N)=Blank  
 SPEC(4,N)=Nozzle exit static pressure or component no. (see SPEC(9,N))  
 SPEC(5,N)=Cv, velocity coefficient or table reference number  
 SPEC(6,N)=0 if converging, =1 if C-D  
 SPEC(7,N)=Area switch, =0 to fix area to input value, =1 to vary area  
     to match flow required  
 SPEC(8,N)=Blank  
 SPEC(9,N)=If SPEC(4,N)=0, set SPEC(9,N) to component number of inlet

Device Type 10: Load

SPEC(1,N)=load horsepower (negative) or table reference number  
 SPEC(2,N)=propeller efficiency or =0  
 SPEC(3,N)=thrust/SHp at SLS

Device Type 11: Shaft

SPEC(1,N)=Actual shaft RPM  
SPEC(2,N)=Gear ratio, first component on shaft. Component rpm/shaft rpm  
SPEC(3,N)=Gear ratio, second component on shaft. Component rpm/shaft rpm  
SPEC(4,N)=Gear ratio, third component on shaft. Component rpm/shaft rpm  
SPEC(5,N)=Gear ratio, fourth component on shaft. Component rpm/shaft rpm  
SPEC(6,N)=Mechanical efficiency of first component  
SPEC(7,N)=Mechanical efficiency of second component  
SPEC(8,N)=Mechanical efficiency of third component  
SPEC(9,N)=Mechanical efficiency of fourth component

Device Type 12: Control

SPCNTL(1,N)=M for the SPEC(M,N) of device N which is to be varied  
SPCNTL(2,N)=N for the component number of the component being varied  
SPCNTL(3,N)=100 if a station property is to be varied  
          =200 if a DATOUT is to be varied  
          =400 if a performance property is to be varied  
SPCNTL(4,N)=Number of station property to be varied  
          =1 weight flow  
          =2 total pressure  
          =3 total temperature  
          =4 fuel to air ratio  
          =5 corrected flow  
          =6 Mach number  
          =7 static pressure  
          =8 interface corrected flow error  
or DATOUT(L) (see output section for values of L for  
          each component)  
or performance property to be varied  
          =1 total engine airflow  
          =2 gross jet thrust  
          =3 fuel flow  
          =4 net jet thrust  
          =5 TSFC  
          =6 net thrust/airflow  
          =7 total inlet drag  
          =8 total brake shaft HP  
          =9 net thrust with installation drags  
          =10 net SFC  
          =11 inlet drag (lip and spillage)  
          =12 boattail drag  
SPCNTL(5,N)=flow station number if SPCNTL(3,N)=100  
          =component number if SPCNTL(3,N)=200  
          =0 if SPCNTL(3,N)=400  
SPCNTL(6,N)=value to be achieved  
SPCNTL(7,N)=tolerance as fraction of value, if =1 default value of  
          0.001 will be used, if =0 control is turned off  
SPCNTL(8,N)=minimum allowable value, if zero ignored  
SPCNTL(9,N)=maximum allowable value, if zero ignored

---

Figure 4.1 shows a sample turbomachinery input file. This is the file that corresponds to the V-6 Compound-Cycle engine discussed later in the first sample case. The only difference between this file and a conventional

```

TEST CASE:  COMBINED CYCLE ENGINE
&D ICEC=0,NCODE=1,LONG=T,NMODES=1, &END
&D MODE=1,
KONFIG(1,1)=1,1,0,2,0,SPEC(1,1)=7.8,4*0,1,5*0,0,0,
KONFIG(1,2)=4,2,0,3,0,SPEC(1,2)=1.8,0,1,1001,1,1002,1,1003,1,
2.,0,.85,1.05,1,
KONFIG(1,3)=7,3,0,12,4,SPEC(1,3)=0.455,0,0,
KONFIG(1,4)=4,4,0,5,0,SPEC(1,4)=1.3,0,1,1004,.5,1005,1,1006,1,
0,0,.79,9.9192,1,
KONFIG(1,5)=6,12,5,13,6,SPEC(1,5)=.02,.02,250.,0.4,1,
KONFIG(1,6)=2,6,0,7,0,SPEC(1,6)=0.1,0,0.000145,6122.,1,18300.,
FARRAY(1,6)=2,1
KONFIG(1,7)=5,7,0,8,0,SPEC(1,7)=4.3,0,1,1007,1,1008,1,1,
0,1,.845,5000,1,
KONFIG(1,8)=2,8,0,9,0,SPEC(1,8)=0,0,0,0,.99,18300.,
FARRAY(1,8)=2,1
KONFIG(1,9)=5,9,0,10,0,SPEC(1,9)=1.8,0,1,1009,1,1010,1,1,
0,1,.848,5000,1,
KONFIG(1,10)=9,10,0,11,0,SPEC(1,10)=0.,1,0.,0.,.9850,1.,0.,
0.,1.,
KONFIG(1,12)=9,13,0,14,0,SPEC(1,12)=0,1,0,0.,0.9850,1.,1.,
0.,1.,
KONFIG(1,13)=11,2,4,7,0,SPEC(1,13)=9*1.
KONFIG(1,14)=11,9,15,0,0,SPEC(1,14)=9*1.
KONFIG(1,15)=10,0,0,0,0,SPEC(1,15)=-200,0,0,
KONFIG(1,16)=12,SPCNTL(1,16)=1,9,100,8,10,0,0,
KONFIG(1,17)=12,SPCNTL(1,17)=1,7,100,8,9,0,0,
KONFIG(1,18)=12,SPCNTL(1,18)=1,4,100,8,7,0,0,
KONFIG(1,20)=12,SPCNTL(1,20)=1,2,100,8,4,0,0,
KONFIG(1,21)=12,SPCNTL(1,21)=1,1,100,8,2,0,0,
KONFIG(1,22)=12,SPCNTL(1,22)=1,13,200,8,13,0,0,
KONFIG(1,23)=12,SPCNTL(1,23)=1,15,200,8,14,0,0,
KONFIG(1,24)=12,SPCNTL(1,24)=3,5,200,8,5,0,1,
KONFIG(1,26)=12,SPCNTL(1,26)=10,2,200,5,2,4.0,0,
&END
&D SPEC(9,16)=1,SPEC(9,17)=1,SPEC(9,18)=1,
SPEC(9,20)=1,SPEC(9,21)=1,SPEC(9,22)=1,SPEC(9,23)=1,
SPEC(9,26)=1, &END
&D SPEC(3,6)=0.00012 &END
&D SPEC(3,6)=0.00010 &END
&D SPEC(3,6)=0.00009 &END
&D SPEC(3,6)=0.00008 &END
&D SPEC(3,6)=0.000075 &END
&D SPEC(3,6)=0.00007 &END
&D SPEC(3,6)=0.000065 &END
&D SPEC(3,6)=0.00006 &END
&D SPEC(3,6)=0.00005 &END
&D SPEC(3,6)=0.00004 &END
&D SPEC(3,6)=0.00003 &END

```

Figure 4.1 Sample Turbomachinery Input File

turbomachinery input file for NNEPEQ is in the line defining the characteristics of component 6, repeated below.

```
KONFIG(1,6)=2,6,0,7,0,SPEC(1,6)=0.1,0,0.000145,6122.,1,18300.,
```

This line appears to define the characteristics of a duct configured as a burner. However, the third item in the SPEC list for a duct is listed as unused by the NNEPEQ manual [3, p.6]. In this case, this variable has been assigned to be an indicator of the presence of a diesel engine in the engine configuration. If the value of this variable is zero, then the component is assumed to be a conventional burner. If the value is non-zero then the component is assumed to be a diesel engine and the numerical value of this variable corresponds to the specified value of fuel injected into each cylinder per cycle (lb/cycle). Further, if the value of the third variable is non-zero, then the value of the fourth variable, ordinarily assigned to be the desired burner outlet temperature, becomes the specified value of diesel engine speed. When the value of the third variable is non-zero, the other variables in the SPEC array are not used.

When developing a data set for a new engine configuration, it is suggested that the third variable be set equal to zero and estimated values of the diesel engine pressure drop and exhaust temperature be assigned. This will allow the turbomachinery portion of the program to be tested without the added complication of the diesel program.

Figure 4.2 shows the form in which data must be entered for the diesel data set. The data is read format-free but must be in the order shown. The variables in the input data set are defined as shown in Table 4.2.

---

Table 4.2 Definitions of Variables in the Diesel Input File

TITLE = Title of run, up to 80 characters  
NCYCLE = 2 if two stroke, = 4 if four stroke engine  
NCYL = number of cylinders  
BORE = Cylinder bore. (inches)  
STROKE = Stroke. (inches)  
CONROD = Connecting rod length. (inches)  
CR = Geometric compression ratio.  
MODE = Piston-cylinder mode. (=1 for conventional piston-cylinder configuration, =2 for opposed piston configuration)  
C1 = Shape parameter for diffusion burning.  
C2 = Crankangle for start of combustion.  
C3 = Combustion duration parameter.  
C4 = Premixed burning fraction.  
C5 = Shape parameter for premixed burning.  
ANNND = Multiplier for Annand heat transfer correlation.  
THEAD = Cylinder head temperature. (deg R)  
TPISTN = Piston temperature. (deg R)  
TSLEEV = Cylinder wall temperature. (deg R)  
MEXH = Exhaust valve or port indicator. (=0 for exhaust ports and =1 for exhaust valves)  
EVO = Exhaust valve or port opening crankangle. (degrees ATDC)  
EVC = Exhaust valve or port closing crankangle. (degrees ATDC)  
MINT = Intake valve or port indicator. (=0 for intake ports and =1 for intake valves)



```

TITLE
NCYCLE      NCYL
BORE        STROKE      CONROD      CR      MODE
C1          C2          C3          C4      C5
ANNND       THEAD       TP1STN     TSLEEV
MEXH        EVO         EVC         MINT     AVO      AVC
NTEXH       CDEXH
ALPHEX(1)   FEXH(1)
ALPHEX(2)   FEXH(2)
.           .
.           .
.           .
ALPHEX(NTEXH) FEXH(NTEXH)
WIDTHI      CDINT

```

Figure 4.2 Format of Diesel Input File

AVO = Intake valve or port opening crankangle. (degrees ATDC)  
 AVC = Intake valve or port closing crankangle. (degrees ATDC)  
 NTEXH = Number of exhaust valve area versus crankangle data pairs  
           to be read in. (for MEXH=1 only)  
 CDEXH = Exhaust valve or port discharge coefficient  
 ALPHEX(I) = Array of crankangles for exhaust valve flow areas. (deg ATDC)  
 FEXH(I) = Array of exhaust valve flow areas. (square inches)  
 WIDTHE = Fraction of the cylinder circumference devoted to exhaust port.  
 NTINT = Number of intake valve area versus crankangle data pairs  
           to be read in. (for MINT=1 only)  
 CDINT = Intake valve or port discharge coefficient  
 ALPHIN(I) = Array of crankangles for intake valve flow areas. (deg ATDC)  
 FINT(I) = Array of intake valve flow areas. (square inches)  
 WIDTHI = Fraction of the cylinder circumference devoted to intake port.

---

When MEXH=1, exhaust valves are being used and the user must specify NTEXH, CDEXH and the arrays of crankangle versus flow area, ALPHEX(I) and FEXH(I). When MEXH=0, exhaust ports are used and the user need only specify WIDTHE and CDEXH. ALPHEX(I) and FEXH(I) are calculated internally. A similar procedure is used when MINT=0. The case illustrated in Table 1 corresponds to an engine that has exhaust valves and intake ports.

## 5 Output from the Combined-Cycle Engine Simulation Program

The output from the combined-cycle engine simulation program consists of two files. The first file characterizes the turbomachinery portion of the engine and is called TURBO.OUT and the second file characterizes the diesel engine and it is called DSL.OUT. The first file is identical to the output file from NNEPEQ [2,3]. The input and output station properties of the diesel engine are reported in this file as if the engine was a burner. This file contains a listing of the properties such as mass flow rate, temperature, pressure, fuel/air ratio, etc. at each flow station for the engine. Then the output variables that are individually defined for each component are presented in a table. The table identifies these variables by their position in the DATOUT array calculated by CCE. The definitions of the elements of this array are provided in Table 5.1. Finally, the file includes a summary of the engine as a whole including air flow rate, fuel consumption, thrust, etc.

-----

Table 5.1 Definition of the elements of the DATOUT array

### Device Type 1: Inlet

DATOUT(1)=inlet drag  
DATOUT(2)=velocity, ft/sec  
DATOUT(3)=velocity, knots  
DATOUT(4)=ram temperature ratio  
DATOUT(5)=ram pressure ratio  
DATOUT(6)=Mach number  
DATOUT(7)=Inlet recovery - exit total pressure/ram pressure  
DATOUT(8)=exit temperature/518.67  
DATOUT(9)=altitude, feet

### Device Type 2: Duct or Diesel engine (Diesel engine output is provided in a separate data file)

DATOUT(1)=Pressure drop/inlet pressure from momentum  
DATOUT(2)=Pressure drop/inlet pressure from SPEC(1,N)  
DATOUT(3)=Pressure ratio at duct inlet used to compute inlet Mach number (Total/Static)  
DATOUT(4)=Fuel flow/duct inlet weight flow  
DATOUT(5)=Cross sectional area - sq inches  
DATOUT(6)=Fuel flow, lb/hr  
DATOUT(7)=Inlet Mach number (if SPEC(2,N) or SPEC(7,N) were specified at the design point)  
DATOUT(8)=Burner efficiency  
DATOUT(9)=Burner outlet temperature (before bypass added)

### Device Type 3: Gas Generator

DATOUT(1)=Generator temperature, deg R  
DATOUT(2)=Assigned generator fuel/oxidizer ratio  
DATOUT(3)=Generator pressure, psia  
DATOUT(4)=Generator fuel weight flow, lb/sec  
DATOUT(5)=Generator oxidant weight flow, lb/sec

DATOUT(6)=Total generator weight flow, lb/hr  
DATOUT(7)=Calculated generator fuel/oxidizer ratio

Device Type 4: Compressor

DATOUT(1)=Horsepower required (negative)  
DATOUT(2)=Physical RPM  
DATOUT(3)=Third dimensional argument on compressor maps  
DATOUT(4)=R value used on maps  
DATOUT(5)=Surge margin in percent  
DATOUT(6)=Corrected speed used to read maps  
DATOUT(7)=Scale factor on corrected flow  
DATOUT(8)=Compressor efficiency  
DATOUT(9)=Compressor pressure ratio

Device Type 5: Turbine

DATOUT(1)=horsepower produced by turbine  
DATOUT(2)=physical rpm  
DATOUT(3)=Third dimension argument value on turbine maps  
DATOUT(4)=pressure ratio used in table lookup  
DATOUT(5)=scale factor on corrected speed  
DATOUT(6)=Corrected speed used in table lookup  
DATOUT(7)=scale factor on corrected flow  
DATOUT(8)=turbine efficiency  
DATOUT(9)=turbine overall pressure ratio

Device Type 6: Heat Exchanger

DATOUT(1)=Pressure drop/inlet pressure for main flow  
DATOUT(2)=Pressure drop/inlet pressure for secondary flow  
DATOUT(3)=Blank  
DATOUT(4)=Effectiveness  
DATOUT(5)=Scale factor on effectiveness  
DATOUT(6)=Calculated temperature difference  
DATOUT(7)=Temperature difference/(T hot - T cold)  
DATOUT(8)=Temperature rise difference (guess value/calculated - 1)

Device Type 7: Splitter

DATOUT(1)=Bypass ratio  
DATOUT(2)=Pressure drop/inlet pressure in primary flow stream  
DATOUT(3)=Pressure drop/inlet pressure in secondary flow stream

Device Type 8: Mixer

DATOUT(1)=Main flow area - sq inches  
DATOUT(2)=Secondary flow area - sq inches  
DATOUT(3)=Total to static pressure ratio at main flow inlet  
DATOUT(4)=Total to static pressure ratio at secondary flow inlet  
DATOUT(5)=Velocity at main flow inlet  
DATOUT(6)=Velocity at secondary flow inlet  
DATOUT(7)=Exit mixed flow velocity  
DATOUT(8)=Static pressure difference between streams  
DATOUT(9)=Total mixed to average static pressure ratio

Device Type 9: Nozzle

DATOUT(1)=Gross jet thrust, lb  
DATOUT(2)=Actual jet velocity, ft/sec  
DATOUT(3)=Total to static pressure ratio at throat

DATOUT(4)=Nozzle exit area, sq inches  
DATOUT(5)=Nozzle throat area, sq inches  
DATOUT(6)=Cd, flow coefficient  
DATOUT(7)=Cv, velocity coefficient  
DATOUT(8)=Critical pressure ratio at throat  
DATOUT(9)=Overall pressure ratio, inlet total to exit static

Device Type 10: Load

DATOUT(1)=Load horsepower (negative)  
DATOUT(2)=Actual shaft rpm  
DATOUT(3)=Propeller thrust

Device Type 11: Shaft

DATOUT(1)=Net shaft horsepower (required-delivered)  
DATOUT(2)=Actual shaft rpm  
DATOUT(3)=Actual shaft rpm of first component  
DATOUT(4)=Actual shaft rpm of second component  
DATOUT(5)=Actual shaft rpm of third component  
DATOUT(6)=Actual shaft rpm of fourth component  
DATOUT(7)=Blank  
DATOUT(8)=Net shaft horsepower/total horsepower

Device Type 12: Control

There is no DATOUT array for controls

-----

The second output file shows the calculated results for the diesel engine. It consists of two parts and is essentially identical to the output file from DSL2 [1]. The first part is a summary of the calculated quantities that characterize the diesel engine's performance. The second part is a listing of the cylinder pressure and temperature and other quantities at 10 degree intervals during the engine cycle. Both parts for the diesel engine output listing are self-explanatory although the symbols are defined in Table 5.2 below. The only difference between the diesel output file from CCE and the output file from DSL2 is that DSL2 gives information about only a single cylinder of a multi-cylinder engine while CCE gives information about the entire engine.

-----

Table 5.2 Symbols Used in Diesel Output File

IMEP = Indicated Mean Effective Pressure  
BMEP = Brake Mean Effective Pressure  
FMEP = Friction Mean Effective Pressure  
IHP = Indicated Horsepower  
BHP = Brake Horsepower  
FHP = Friction Horsepower  
ISFC = Indicated Specific Fuel Consumption  
BSFC = Brake Specific Fuel Consumption

EQUIVALENCE RATIO DURING COMPRESSION = This is the equivalence ratio in the cylinder at the start of the compression process. It is an indicator of the amount of residual gas left from the previous

cycle.

EQUIVALENCE RATIO AT EVO = This is the equivalence ratio in the cylinder when the exhaust valve (or port) opens. It is an indicator of how much of the oxygen that entered the cylinder is still unused.

EQUIVLANCE RATIO BASED ON FUEL AND AIR FLOW RATES = This is the equivalence ratio calculated from the fuel and air flow rates supplied to the engine. In two-stroke engines it will generally be less than that in the cylinder at EVO due to the diluting effect of the extra air supplied to scavenge the exhaust products from the cylinder.

CA = Crankangle

PCYL = Cylinder pressure

TCYL = Cylinder temperature

PHICYL = Equivalence ratio in the cylinder

MCYL = Total mass in the cylinder

MDOTIN = Mass flow rate into cylinder through intake valve (or port)

MDOTOUT = Mass flow rate out of cylinder through exhaust valve (or port)

BALANCE = Monitor on the overall cylinder energy balance. (Generally less than 0.005)

## 6 Sample Cases

### 6.1 Case Number One: V-6 Diesel Engine With Aftercooling

This case is derived from the combined-cycle engine proposed by Castor of the Garrett Turbine Engine Company [7]. This engine assumes a 6-cylinder diesel engine running at 6122 rpm coupled to turbomachinery that provides supercharging air at 150 psia to the diesel as well as power recovery from the exhaust. The overall engine power is designed to be 1000 hp. The engine specifications are shown in the table below.

---

Table 6.1 V-6 Engine Specifications

Two-stroke, V-6 Diesel Engine, uniflow scavenged	
Bore	3.10 inches
Stroke	2.94 inches
Compression ratio	9.17 (geometric)
At design point (14.7 psia, 519 deg R intake conditions)	
Inlet manifold pressure	150 psia
Inlet manifold temperature	896 deg R
Compressor efficiency	0.79
Turbine efficiencies	0.845, 0.848
Exhaust opens	90 deg ATDC
Exhaust closes	239 deg ATDC
Intake opens	126 deg ATDC
Intake closes	234 deg ATDC

---

The block diagram shown in Figure 6.1 shows the combined-cycle engine configuration used to model the engine. The numbers enclosed by circles identify "flow stations" in the engine and the numbers and names in the rectangles identify components. The design includes a low pressure fan to supply air through a splitter to both the high pressure compressor and an air-to-air aftercooler. The diesel engine receives air from the aftercooler and discharges to a turbine that drives the fan and compressor. Exhaust products pass from this turbine through a duct and into a power turbine. The duct was included so that reheating of the exhaust products before entering the power turbine could be investigated. However, this feature is not used here.

The engine simulation program was adjusted to match the performance of the engine proposed by Castor [7] at the design point. Then, with the diesel speed held constant, the fuel flow rate was reduced to provide information about part load performance. Figure 6.2 shows the turbomachinery input data file used by CCE. The corresponding diesel input file is shown in Figure 6.3.

Table 6.2 shows a comparison between the performance characteristics listed by Castor [7] and those provided by CCE.

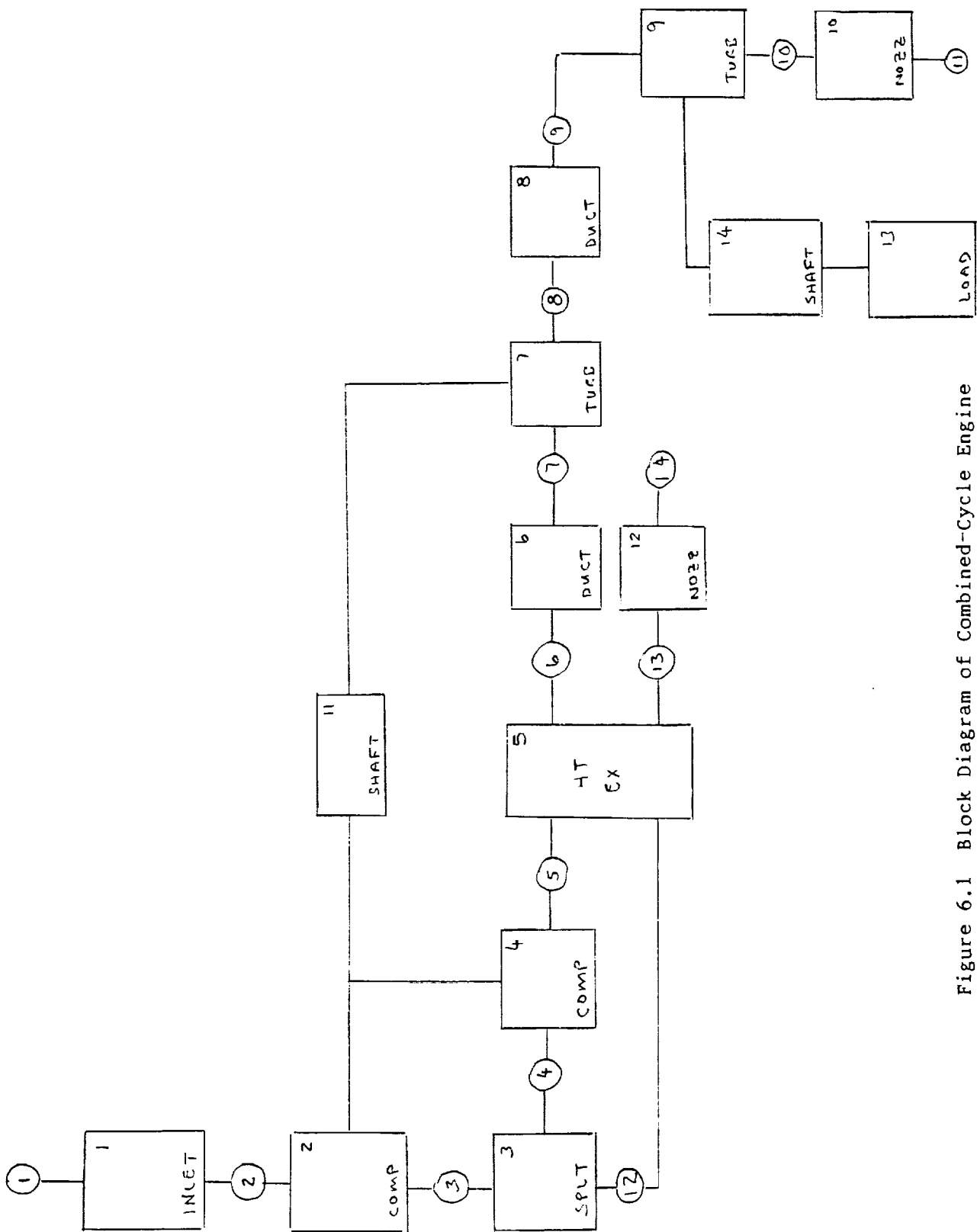


Figure 6.1 Block Diagram of Combined-Cycle Engine



```

TEST CASE:  COMBINED CYCLE ENGINE
&D ICEC=0,NCODE=1,LONG=T,NMODES=1, &END
&D MODE=1,
KONFIG(1,1)=1,1,0,2,0,SPEC(1,1)=7.8,4*0,1,5*0,0,0,
KONFIG(1,2)=4,2,0,3,0,SPEC(1,2)=1.8,0,1,1001,1,1002,1,1003,1,
2.,0,.85,1.05,1,
KONFIG(1,3)=7,3,0,12,4,SPEC(1,3)=0.455,0,0,
KONFIG(1,4)=4,4,0,5,0,SPEC(1,4)=1.3,0,1,1004,.5,1005,1,1006,1,
0,0,.79,9.9192,1,
KONFIG(1,5)=6,12,5,13,6,SPEC(1,5)=.02,.02,250.,0.4,1,
KONFIG(1,6)=2,6,0,7,0,SPEC(1,6)=0.1,0,0.000145,6122.,1,18300.,
FARRAY(1,6)=2,1
KONFIG(1,7)=5,7,0,8,0,SPEC(1,7)=4.3,0,1,1007,1,1008,1,1,
0,1,.845,5000,1,
KONFIG(1,8)=2,8,0,9,0,SPEC(1,8)=0,0,0,0,.99,18300.,
FARRAY(1,8)=2,1
KONFIG(1,9)=5,9,0,10,0,SPEC(1,9)=1.8,0,1,1009,1,1010,1,1,
0,1,.848,5000,1,
KONFIG(1,10)=9,10,0,11,0,SPEC(1,10)=0.,1,0.,0.,.9850,1.,0.,
0.,1.,
KONFIG(1,12)=9,13,0,14,0,SPEC(1,12)=0,1,0,0.,0.9850,1.,1.,
0.,1.,
KONFIG(1,13)=11,2,4,7,0,SPEC(1,13)=9*1.
KONFIG(1,14)=11,9,15,0,0,SPEC(1,14)=9*1.
KONFIG(1,15)=10,0,0,0,0,SPEC(1,15)=-200,0,0,
KONFIG(1,16)=12,SPCNTL(1,16)=1,9,100,8,10,0,0,
KONFIG(1,17)=12,SPCNTL(1,17)=1,7,100,8,9,0,0,
KONFIG(1,18)=12,SPCNTL(1,18)=1,4,100,8,7,0,0,
KONFIG(1,20)=12,SPCNTL(1,20)=1,2,100,8,4,0,0,
KONFIG(1,21)=12,SPCNTL(1,21)=1,1,100,8,2,0,0,
KONFIG(1,22)=12,SPCNTL(1,22)=1,13,200,8,13,0,0,
KONFIG(1,23)=12,SPCNTL(1,23)=1,15,200,8,14,0,0,
KONFIG(1,24)=12,SPCNTL(1,24)=3,5,200,8,5,0,1,
KONFIG(1,26)=12,SPCNTL(1,26)=10,2,200,5,2,4,0,0,
&END
&D SPEC(9,16)=1,SPEC(9,17)=1,SPEC(9,18)=1,
SPEC(9,20)=1,SPEC(9,21)=1,SPEC(9,22)=1,SPEC(9,23)=1,
SPEC(9,26)=1, &END
&D SPEC(3,6)=0.00012 &END
&D SPEC(3,6)=0.00010 &END
&D SPEC(3,6)=0.00009 &END
&D SPEC(3,6)=0.00008 &END
&D SPEC(3,6)=0.000075 &END
&D SPEC(3,6)=0.00007 &END
&D SPEC(3,6)=0.000065 &END
&D SPEC(3,6)=0.00006 &END
&D SPEC(3,6)=0.00005 &END
&D SPEC(3,6)=0.00004 &END
&D SPEC(3,6)=0.00003 &END

```

Figure 6.2 Turbomachinery Input Data File for Sample Case 1

```

TWO-STROKE, V-6 ENGINE WITH UNIFLOW SCAVENGING
2 6
3.100 2.940 7.168 9.1712 1
1.3 345. 75. 0.0 3.5
0.55 1460. 1460. 1460.
1 90. 239. 0 126. 234.
13 0.8864
90.00 0.0000
100.97 0.1343
115.00 0.5242
121.61 0.8514
131.00 1.2946
142.25 1.5293
162.89 1.6924
180.95 1.6000
194.00 1.3291
201.59 1.0338
209.00 0.6638
222.23 0.2617
239.00 0.0000
0.5542 0.8

```

Figure 6.3 Diesel Input Data File for Sample Case 1

Table 6.2 Combined-Cycle Engine Performance Comparison

	Castor [7]	CCE
Brake mean effective pressure (psi)	393	391.7
Brake power (diesel only) (HP)	810	806.5
Brake power (power turbine) (HP)	241	200.0
Brake power (total) (HP)	1051	1006.5
Brake specific fuel consumption (lb/hp-hr)	0.328	0.317
Maximum cylinder pressure (psia)	3362	3140.
Air flow rate (lb/sec)	2.44	2.44
Turbine inlet temperature (deg R)	2214	2208.
Equivalence ratio	0.68	0.674

The diesel output file for the design point case is shown in Figure 6.4 and the turbomachinery output file is shown in Figure 6.5. The overall BSFC shown in Table 6.2 is calculated from the power produced by both and diesel and power turbine and the fuel consumed by the diesel. It is not calculated within the program CCE.

The turbomachinery input file shown in Figure 6.2 specifies that the program will evaluate the design point case as well as 11 off-design cases. Although performance may only be desired at a few off-design points, in practice it is usually necessary to run the program at several intermediate points. The program uses an iterative procedure to solve the turbomachinery matching problem. The previous case conditions are used as initial estimates for the next case. If the change in conditions from one case to the next is too large, the program will be unable to converge. When this is a problem, the solution is usually as simple as inserting several intermediate points between the desired cases.

In this case, the part load, rated speed performance was investigated. Table 6.3 shows the effect of reducing the amount of fuel injected on the power split between the diesel engine and the power turbine as well as the effect on the overall brake specific fuel consumption.

Table 6.3 Effect of fuel flow rate on Combined-Cycle Engine Performance

Fuel injected per cylinder per cycle (lb)	BMEP (psi)	Brake Power (diesel) (HP)	Brake Power (turbine) (HP)	BSFC (lb/hp-hr)
0.000145	391.7	806.5	200.0	0.317
0.00012	325.7	670.6	156.6	0.320
0.00010	271.1	558.2	125.0	0.322
0.00008	214.2	441.0	89.6	0.332
0.00006	156.2	321.5	55.7	0.351
0.00004	97.1	200.0	26.4	0.389

TWO-STROKE, V-6 ENGINE WITH UNIFLOW SCAVENGING  
 BORE 3.100 INCHES  
 STROKE 2.940 INCHES  
 CONNECTING ROD 7.168 INCHES  
 GEOMETRIC COMPRESSION RATIO 9.17  
 EFFECTIVE COMPRESSION RATIO 7.50  
 NUMBER OF CYLINDERS 6  
 SWEEP VOLUME (TOTAL) 133.141 CUBIC INCHES  
 ENGINE SPEED 6122. RPM  
 MEAN PISTON SPEED 3000. FT/MIN  
 SUPPLY AIR PRESSURE 150.00 PSIA  
 SUPPLY AIR TEMPERATURE 885.86 DEG R  
 EXHAUST PRESSURE 133.74 PSIA

PORT TIMING: INTAKE OPEN 126.  
 INTAKE CLOSE 234.  
 EXHAUST OPEN 90.  
 EXHAUST CLOSE 239.

FUEL FLOW RATE 0.0888 LBM/SEC FUEL INJECTED/CYCLE 0.000145 LBM/CYCLE  
 AIR FLOW RATE 2.4384 LBM/SEC AIR INDUCTED/CYCLE 0.003983 LBM/CYCLE

IMEP 419.7 PSI IHP 864.2 HP  
 BMEP 391.7 PSI BHP 806.5 HP  
 FMEP 28.0 PSI FHP 57.7 HP

ISFC 0.3698 LBM/HP-HR  
 BSFC 0.3962 LBM/HP-HR

INDICATED THERMAL EFFICIENCY 0.3779  
 BRAKE THERMAL EFFICIENCY 0.3527

MAXIMUM PRESSURE 3140.0 PSIA AT 371.3 DEG  
 MAXIMUM TEMPERATURE 4020.8 DEG R AT 390.0 DEG  
 MAXIMUM RATE OF PRESS RISE 60.50 PSI/DEG AT 355.3 DEG

PURITY 0.8371  
 SCAVENGING EFFICIENCY 0.7759  
 TRAPPING EFFICIENCY 0.7763  
 CHARGING EFFICIENCY 0.5268  
 DELIVERY RATIO 0.6787  
 RESIDUAL FRACTION 0.2366

EQUIVALENCE RATIO DURING COMPRESSION 0.1539  
 EQUIVALENCE RATIO AT EVO 0.6738  
 EQUIVALENCE RATIO BASED ON FUEL AND  
 AIR FLOW RATES (EXHAUST) 0.5234

% FUEL ENERGY TO HEAT LOSS 6.67 %  
 % FUEL ENERGY TO WORK 37.79 %  
 % FUEL ENERGY TO EXHAUST 55.54 %

EXHAUST TEMPERATURE 2208.0 DEG R

Figure 6.4 Diesel Output File for Sample Case 1

CA	PCYL	TCYL	PHICYL	MCYL	MDOTIN	MDOTOUT	BALANCE
90.00	545.3	3047.8	0.6738	0.004199	0.000000	0.000000	0.00000
100.00	458.6	2930.4	0.6738	0.004137	0.000000	0.000013	0.00000
110.00	377.1	2803.5	0.6738	0.003929	0.000000	0.000030	0.00000
120.00	292.8	2647.8	0.6738	0.003507	0.000000	0.000055	0.00000
126.00	241.0	2534.3	0.6738	0.003145	0.000000	0.000064	0.00000
130.00	205.7	2445.0	0.6738	0.001537	-0.000016	0.000063	0.00000
140.00	142.8	2206.3	0.6483	0.001459	0.000031	0.000029	0.00000
150.00	137.0	1879.3	0.4754	0.001967	0.000063	0.000019	0.00000
160.00	138.7	1641.3	0.3476	0.002667	0.000075	0.000024	-0.00003
170.00	140.3	1485.7	0.2682	0.003438	0.000078	0.000028	-0.00001
175.17	141.0	1427.9	0.2395	0.003842	0.000078	0.000029	-0.00002
180.00	142.9	1388.3	0.2186	0.004010	0.000070	0.000040	0.00006
180.00	142.9	1388.3	0.2186	0.004011	0.000070	0.000040	-0.00003
190.00	144.9	1324.4	0.1869	0.004239	0.000058	0.000040	-0.00003
200.00	146.8	1282.8	0.1662	0.004360	0.000041	0.000034	-0.00004
210.00	149.3	1263.9	0.1553	0.004377	0.000016	0.000021	-0.00005
220.00	150.4	1263.9	0.1539	0.004239	-0.000006	0.000011	-0.00004
230.00	153.9	1272.1	0.1539	0.004088	-0.000006	0.000005	-0.00004
240.00	166.5	1299.2	0.1539	0.004051	0.000000	0.000000	-0.00005
250.00	186.2	1338.1	0.1539	0.004051	0.000000	0.000000	-0.00005
260.00	213.1	1386.2	0.1539	0.004051	0.000000	0.000000	-0.00005
270.00	250.2	1445.0	0.1539	0.004051	0.000000	0.000000	-0.00005
280.00	302.2	1516.5	0.1539	0.004051	0.000000	0.000000	-0.00005
290.00	376.5	1603.1	0.1539	0.004051	0.000000	0.000000	-0.00005
300.00	484.8	1707.4	0.1539	0.004051	0.000000	0.000000	-0.00005
310.00	645.6	1832.0	0.1539	0.004051	0.000000	0.000000	-0.00005
320.00	886.0	1978.0	0.1539	0.004051	0.000000	0.000000	-0.00005
330.00	1236.4	2141.6	0.1539	0.004051	0.000000	0.000000	-0.00005
340.00	1698.9	2307.1	0.1539	0.004051	0.000000	0.000000	-0.00005
350.00	2198.8	2476.1	0.1610	0.004053	0.000000	0.000000	-0.00005
360.00	2785.0	2904.7	0.2355	0.004073	0.000000	0.000000	-0.00004
370.00	3133.9	3482.7	0.3746	0.004112	0.000000	0.000000	-0.00004
380.00	2935.8	3898.6	0.5170	0.004152	0.000000	0.000000	-0.00005
390.00	2387.7	4020.8	0.6125	0.004178	0.000000	0.000000	-0.00004
400.00	1810.2	3918.3	0.6565	0.004191	0.000000	0.000000	-0.00004
410.00	1353.3	3719.8	0.6705	0.004195	0.000000	0.000000	-0.00004
420.00	1030.0	3512.9	0.6736	0.004195	0.000000	0.000000	-0.00004
430.00	807.7	3330.3	0.6741	0.004196	0.000000	0.000000	-0.00004
440.00	653.8	3176.9	0.6741	0.004196	0.000000	0.000000	-0.00005

Figure 6.4 - - continued

CASE IDENTIFICATION TEST CASE: COMBINED CYCLE ENGINE

STATION PROPERTY OUTPUT DATA

FLOW STATION NAME-APP?	WEIGHT FLOW STATP1	TOTAL PRESSURE STATP2	TOTAL TEMPERATURE STATP3	FUEL/AIR RATIO STATP4	REFERRED FLOW STATP5	MACH NUMBER STATP6	STATIC PRESSURE STATP7	INTERFACE CORRECTED FLOW ERROR STATP8
1-1	0.78000D+01	0.14696D+02	0.51867D+03	0.00000D+00	0.77998D+01	0.00000D+00	0.00000D+00	0.00000D+00
2-2	0.78000D+01	0.14696D+02	0.51867D+03	0.00000D+00	0.77998D+01	0.00000D+00	0.00000D+00	0.00000D+00
3-3	0.78000D+01	0.15431D+02	0.52722D+03	0.00000D+00	0.74894D+01	0.00000D+00	0.00000D+00	0.00000D+00
4-4	0.24392D+01	0.15431D+02	0.52722D+03	0.00000D+00	0.23421D+01	0.00000D+00	0.00000D+00	0.00000D+00
5-5	0.24392D+01	0.15306D+03	0.11319D+04	0.00000D+00	0.34595D+00	0.00000D+00	0.00000D+00	0.00000D+00
6-6	0.24392D+01	0.15000D+03	0.88586D+03	0.00000D+00	0.31231D+00	0.00000D+00	0.00000D+00	0.00000D+00
7-7	0.25280D+01	0.13372D+03	0.22080D+04	0.36404D-01	0.57320D+00	0.00000D+00	0.00000D+00	0.00000D+00
8-8	0.25280D+01	0.34255D+02	0.16982D+04	0.36404D-01	0.19624D+01	0.00000D+00	0.00000D+00	0.00000D+00
9-9	0.25280D+01	0.34255D+02	0.16982D+04	0.36404D-01	0.19624D+01	0.00000D+00	0.00000D+00	0.00000D+00
10-10	0.25280D+01	0.18616D+02	0.14999D+04	0.36404D-01	0.33936D+01	0.60301D+00	0.14696D+02	0.00000D+00
11-11	0.25280D+01	0.18616D+02	0.14999D+04	0.36404D-01	0.33936D+01	0.59396D+00	0.14696D+02	0.00000D+00
12-12	0.53608D+01	0.15431D+02	0.52722D+03	0.00000D+00	0.51474D+01	0.00000D+00	0.00000D+00	0.00000D+00
13-13	0.53608D+01	0.15122D+02	0.64319D+03	0.00000D+00	0.58014D+01	0.20293D+00	0.14696D+02	0.00000D+00
14-14	0.53608D+01	0.15122D+02	0.64319D+03	0.00000D+00	0.58014D+01	0.19989D+00	0.14696D+02	0.00000D+00

COMPONENT OUTPUT DATA

COMPONENT NO. TYPE	DATOUT1	DATOUT2	DATOUT3	DATOUT4	DATOUT5	DATOUT6	DATOUT7	DATOUT8	DATOUT9
1 INLET	0.00000D+00	0.00000D+00	0.00000D+00	0.10000D+01	0.10000D+01	0.00000D+00	0.10000D+01	0.10000D+01	0.00000D+00
2 COMPRESR	-0.22630D+02	0.10000D+01	0.20000D+01	0.18000D+01	0.35632D+01	0.10000D+01	0.72456D+01	0.85000D+00	0.10500D+01
3 SPLITTER	0.45500D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
4 COMPRESR	-0.51091D+03	0.10000D+01	0.00000D+00	0.13000D+01	0.30222D+02	0.10000D+01	0.22851D+01	0.79000D+00	0.99192D+01
5 HEAT EXC	0.20000D-01	0.20000D-01	0.00000D+00	0.40000D+00	0.10000D+01	0.11597D+03	0.19180D+00	-0.11102D-15	0.00000D+00
6 DUCT B	0.00000D+00	0.00000D+00	0.00000D+00	0.36404D-01	0.00000D+00	0.31967D+03	0.00000D+00	0.10000D+01	0.22080D+04
7 TURBINE	0.53354D+03	0.10000D+01	0.10000D+01	0.43000D+01	0.96935D-04	0.50000D+04	0.29096D-01	0.84500D+00	0.39038D+01
8 DUCT B	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
9 TURBINE	0.20000D+03	0.10000D+01	0.10000D+01	0.18000D+01	0.11053D-03	0.50000D+04	0.32239D-01	0.84800D+00	0.18401D+01
10 NOZZLE	0.84124D+02	0.10707D+04	0.12667D+01	0.11939D+02	0.11939D+02	0.10000D+01	0.98500D+00	0.18562D+01	0.12667D+01
12 NOZZLE	0.41209D+02	0.24732D+03	0.10290D+01	0.49441D+02	0.49441D+02	0.10000D+01	0.98500D+00	0.18931D+01	0.10290D+01
13 SHAFT	0.00000D+00	0.10000D+01	0.10000D+01	0.10000D+01	0.10000D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
14 SHAFT	0.00000D+00	0.10000D+01	0.10000D+01	0.10000D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
15 LOAD	-0.20000D+03	0.10000D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00

MACH=	0.0000	ALTITUDE=	0.	RECOVERY=	1.0000	8 ITERATIONS	20 PASSES
AIRFLOW (LB/SEC)	125.33	TSFC	7.80	GROSS THRUST	125.33	FUEL FLOW (LB/HR)	319.67
NET THRUST					2.5505	NET THRUST/AIRFLOW	16.0684
TOTAL INLET DRAG	125.33	INSTALLED TSFC	0.00	TOTAL BRAKE SHAFT HP	2.5505	BOATTAIL DRAG	0.00
INSTALLED THRUST						SPILLAGE + LIP DRAG	0.00

Figure 6.5 Turbomachinery Output File for Sample Case 1

The brake specific fuel consumption stays relatively constant down to about 65% of full power and then starts to increase. This can be attributed to the influence of the power recovery from the exhaust turbine which tends to keep the BSFC low even at part load.

## 6.2 Case Number Two: Opposed Piston 3-Cylinder Diesel Engine

This case is similar to the combined-cycle engine described in case number 1. The purpose of the engine and its design requirements are the same. The diesel input data file, shown in Figure 6.6, is the same as for the V-6 engine except for the volume mode indicator that denotes an opposed piston configuration. Also, the exhaust port width is specified instead of the exhaust valve area profile. The turbomachinery input file shown in Figure 6.7 is the same as the earlier case except that the fuel injected per cylinder is doubled to reflect the increased air flow provided per cylinder.

The design point output files are shown in Figures 6.8 and 6.9, respectively. In general, the differences between the two engines are small. There are almost no differences in the turbomachinery. The most significant differences in the diesel engine are the peak pressure and the equivalence ratio. The difference in peak pressure probably results from the difference in effective compression ratio that occurs when the exhaust port of the opposed piston engine closes 21 degrees later than the exhaust valve in the V-6 engine. The difference in equivalence ratio is probably due to differences in scavenging that also relate to changes in valve/port timing. No attempt was made to optimize the port timing. Performance improvements beyond that shown may be possible.

```
TWO-STROKE, OPPOSED PISTON 3-CYL ENGINE
2 3
3.100 2.940 7.168 9.1712 2
1.5 345. 65. 0.0 3.5
0.55 1460. 1460. 1460.
0 100. 260. 0 125. 235.
0.5542 0.8
0.5542 0.8
```

Figure 6.6 Diesel Input Data File for Sample Case 2



```

TEST CASE: COMBINED CYCLE ENGINE
&D ICEC=0,NCODE=1,LONG=T,NMODES=1, &END
&D MODE=1,
KONFIG(1,1)=1,1,0,2,0,SPEC(1,1)=7.8,4*0,1,5*0,0,0,
KONFIG(1,2)=4,2,0,3,0,SPEC(1,2)=1.8,0,1,1001,1,1002,1,1003,1,
2.,0,.85,1.05,1,
KONFIG(1,3)=7,3,0,12,4,SPEC(1,3)=0.455,0,0,
KONFIG(1,4)=4,4,0,5,0,SPEC(1,4)=1.3,0,1,1004,.5,1005,1,1006,1,
0,0,.79,9.9192,1,
KONFIG(1,5)=6,12,5,13,6,SPEC(1,5)=.02,.02,250.,0.4,1,
KONFIG(1,6)=2,6,0,7,0,SPEC(1,6)=0.1,0,0.00029,6122.,1,18300.,
FARRAY(1,6)=2,1
KONFIG(1,7)=5,7,0,8,0,SPEC(1,7)=4.3,0,1,1007,1,1008,1,1,
0,1,.845,5000,1,
KONFIG(1,8)=2,8,0,9,0,SPEC(1,8)=0,0,0,0,.99,18300.,
FARRAY(1,8)=2,1
KONFIG(1,9)=5,9,0,10,0,SPEC(1,9)=1.8,0,1,1009,1,1010,1,1,
0,1,.848,5000,1,
KONFIG(1,10)=9,10,0,11,0,SPEC(1,10)=0.,1,0.,0.,.9850,1.,0.,
0.,1.,
KONFIG(1,12)=9,13,0,14,0,SPEC(1,12)=0,1,0,0.,0.9850,1.,1.,
0.,1.,
KONFIG(1,13)=11,2,4,7,0,SPEC(1,13)=9*1.
KONFIG(1,14)=11,9,15,0,0,SPEC(1,14)=9*1.
KONFIG(1,15)=10,0,0,0,0,SPEC(1,15)=-200,0,0,
KONFIG(1,16)=12,SPCNTL(1,16)=1,9,100,8,10,0,0,
KONFIG(1,17)=12,SPCNTL(1,17)=1,7,100,8,9,0,0,
KONFIG(1,18)=12,SPCNTL(1,18)=1,4,100,8,7,0,0,
KONFIG(1,20)=12,SPCNTL(1,20)=1,2,100,8,4,0,0,
KONFIG(1,21)=12,SPCNTL(1,21)=1,1,100,8,2,0,0,
KONFIG(1,22)=12,SPCNTL(1,22)=1,13,200,8,13,0,0,
KONFIG(1,23)=12,SPCNTL(1,23)=1,15,200,8,14,0,0,
KONFIG(1,24)=12,SPCNTL(1,24)=3,5,200,8,5,0,1,
KONFIG(1,26)=12,SPCNTL(1,26)=10,2,200,5,2,4.0,0,
&END
&D SPEC(9,16)=1,SPEC(9,17)=1,SPEC(9,18)=1,
SPEC(9,20)=1,SPEC(9,21)=1,SPEC(9,22)=1,SPEC(9,23)=1,
SPEC(9,26)=1, &END
&D SPEC(3,6)=0.00024 &END
&D SPEC(3,6)=0.00020 &END
&D SPEC(3,6)=0.00018 &END
&D SPEC(3,6)=0.00016 &END
&D SPEC(3,6)=0.00014 &END
&D SPEC(3,6)=0.00012 &END
&D SPEC(3,6)=0.00010 &END
&D SPEC(3,6)=0.00009 &END
&D SPEC(3,6)=0.00008 &END
&D SPEC(3,6)=0.00007 &END
&D SPEC(3,6)=0.00006 &END

```

Figure 6.7 Turbomachinery Input Data File for Sample Case 2

TWO-STROKE, OPPOSED PISTON 3-CYL ENGINE

BORE	3.100 INCHES
STROKE	2.940 INCHES
CONNECTING ROD	7.168 INCHES
GEOMETRIC COMPRESSION RATIO	9.17
EFFECTIVE COMPRESSION RATIO	6.21
NUMBER OF CYLINDERS	3
SWEPT VOLUME (TOTAL)	133.141 CUBIC INCHES
ENGINE SPEED	6122. RPM
MEAN PISTON SPEED	3000. FT/MIN
SUPPLY AIR PRESSURE	150.00 PSIA
SUPPLY AIR TEMPERATURE	885.86 DEG R
EXHAUST PRESSURE	129.66 PSIA

PORT TIMING:	INTAKE OPEN	125.
	INTAKE CLOSE	235.
	EXHAUST OPEN	100.
	EXHAUST CLOSE	260.

FUEL FLOW RATE	0.0888 LBM/SEC	FUEL INJECTED/CYCLE	0.000290 LBM/CYCLE
AIR FLOW RATE	2.4390 LBM/SEC	AIR INDUCTED/CYCLE	0.007968 LBM/CYCLE

IMEP	421.4 PSI	IHP	867.8 HP
BMEP	393.4 PSI	BHP	810.1 HP
FMEP	28.0 PSI	FHP	57.7 HP

ISFC	0.3683 LBM/HP-HR
BSFC	0.3945 LBM/HP-HR

INDICATED THERMAL EFFICIENCY	0.3795
BRAKE THERMAL EFFICIENCY	0.3542

MAXIMUM PRESSURE	2679.4 PSIA	AT 374.5 DEG
MAXIMUM TEMPERATURE	4662.5 DEG R	AT 387.4 DEG
MAXIMUM RATE OF PRESS RISE	62.01 PSI/DEG	AT 359.4 DEG

PURITY	0.8287
SCAVENGING EFFICIENCY	0.8058
TRAPPING EFFICIENCY	0.6096
CHARGING EFFICIENCY	0.4138
DELIVERY RATIO	0.6788
RESIDUAL FRACTION	0.1978

EQUIVALENCE RATIO DURING COMPRESSION	0.1620
EQUIVALENCE RATIO AT EVO	0.8580
EQUIVALENCE RATIO BASED ON FUEL AND AIR FLOW RATES (EXHAUST)	0.5233

% FUEL ENERGY TO HEAT LOSS	4.70 %
% FUEL ENERGY TO WORK	37.95 %
% FUEL ENERGY TO EXHAUST	57.35 %

EXHAUST TEMPERATURE	2187.3 DEG R
---------------------	--------------

Figure 6.8 Diesel Output File for Sample Case 2

CA	PCYL	TCYL	PHICYL	MCYL	MDOTIN	MDOTOUT	BALANCE
100.00	405.4	3378.9	0.8580	0.006350	0.000000	0.000000	0.00000
110.00	325.2	3221.2	0.8580	0.005904	0.000000	0.000081	0.00000
120.00	230.3	2990.1	0.8580	0.004890	0.000000	0.000113	0.00000
125.00	188.2	2862.4	0.8580	0.004325	0.000000	0.000110	-0.00003
130.00	153.4	2737.5	0.8580	0.002139	-0.000005	0.000085	-0.00003
140.00	129.7	2439.2	0.7413	0.002454	0.000054	0.000006	-0.00003
150.00	130.1	2138.4	0.5741	0.003134	0.000080	0.000018	-0.00004
160.00	130.6	1883.6	0.4417	0.004036	0.000099	0.000027	-0.00001
170.00	131.0	1694.0	0.3485	0.005084	0.000109	0.000035	0.00000
180.00	131.3	1558.5	0.2846	0.006199	0.000112	0.000039	0.00009
185.45	131.5	1502.3	0.2587	0.006808	0.000111	0.000041	0.00011
190.00	132.6	1465.4	0.2406	0.007010	0.000105	0.000069	0.00026
190.00	132.5	1465.5	0.2407	0.007010	0.000105	0.000069	0.00010
200.00	133.3	1395.9	0.2090	0.007278	0.000093	0.000075	0.00010
210.00	133.7	1344.6	0.1862	0.007371	0.000074	0.000073	0.00009
220.00	134.0	1310.2	0.1710	0.007286	0.000049	0.000067	0.00009
230.00	134.1	1292.2	0.1630	0.007014	0.000018	0.000054	0.00004
240.00	134.6	1291.4	0.1620	0.006590	0.000000	0.000041	0.00004
250.00	139.5	1304.1	0.1620	0.006230	0.000000	0.000030	0.00005
260.00	153.7	1337.8	0.1620	0.006055	0.000000	0.000000	0.00005
270.00	180.6	1395.1	0.1620	0.006055	0.000000	0.000000	0.00005
280.00	218.2	1464.8	0.1620	0.006055	0.000000	0.000000	0.00005
290.00	272.0	1549.4	0.1620	0.006055	0.000000	0.000000	0.00005
300.00	350.4	1651.3	0.1620	0.006055	0.000000	0.000000	0.00005
310.00	467.0	1773.2	0.1620	0.006055	0.000000	0.000000	0.00005
320.00	641.5	1916.2	0.1620	0.006055	0.000000	0.000000	0.00004
330.00	896.2	2077.0	0.1620	0.006055	0.000000	0.000000	0.00004
340.00	1233.0	2240.4	0.1620	0.006055	0.000000	0.000000	0.00004
350.00	1602.0	2413.7	0.1698	0.006058	0.000000	0.000000	0.00004
360.00	2152.1	2997.4	0.2748	0.006102	0.000000	0.000000	0.00007
370.00	2633.6	3890.5	0.4889	0.006191	0.000000	0.000000	0.00012
380.00	2569.9	4518.5	0.6982	0.006278	0.000000	0.000000	0.00010
390.00	2091.8	4658.4	0.8140	0.006327	0.000000	0.000000	0.00013
400.00	1567.7	4489.7	0.8510	0.006342	0.000000	0.000000	0.00012
410.00	1164.8	4237.9	0.8576	0.006345	0.000000	0.000000	0.00012
420.00	886.5	4002.8	0.8583	0.006345	0.000000	0.000000	0.00012
430.00	696.6	3802.9	0.8584	0.006345	0.000000	0.000000	0.00011
440.00	565.1	3635.7	0.8584	0.006345	0.000000	0.000000	0.00011
450.00	472.2	3496.6	0.8584	0.006345	0.000000	0.000000	0.00011

Figure 6.8 - - continued

# STATION PROPERTY OUTPUT DATA

FLOW STATION NAME-ARP?	WEIGHT FLOW	TOTAL PRESSURE STATP2	TOTAL TEMPERATURE STATP3	FUEL/AIR RATIO STATP4	REFERRED FLOW STATP5	MACH NUMBER STATP6	STATIC PRESSURE STATP7	INTERFACE FLOW ERROR STATP8	CORRECTED FLOW ERROR STATP8
1-1	0.78000D+01	0.14896D+02	0.51867D+03	0.00000D+00	0.77998D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
2-2	0.78000D+01	0.14896D+02	0.51867D+03	0.00000D+00	0.77998D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
3-3	0.78000D+01	0.14896D+02	0.51867D+03	0.00000D+00	0.77998D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
4-4	0.24392D+01	0.15431D+02	0.52722D+03	0.00000D+00	0.74894D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
5-5	0.24392D+01	0.15431D+02	0.52722D+03	0.00000D+00	0.74894D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
6-6	0.24392D+01	0.15306D+03	0.11319D+04	0.00000D+00	0.23421D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
7-7	0.24392D+01	0.15000D+03	0.88586D+03	0.00000D+00	0.31231D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
8-8	0.25279D+01	0.12965D+03	0.21873D+04	0.36395D-01	0.58842D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
9-9	0.25279D+01	0.32695D+02	0.16765D+04	0.36395D-01	0.20428D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
10-10	0.25279D+01	0.32695D+02	0.16765D+04	0.36395D-01	0.20428D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
11-11	0.25279D+01	0.17615D+02	0.14777D+04	0.36395D-01	0.35598D+01	0.52638D+00	0.14696D+02	0.00000D+00	0.00000D+00
12-12	0.53608D+01	0.15431D+02	0.52722D+03	0.00000D+00	0.51474D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
13-13	0.53608D+01	0.15122D+02	0.64319D+03	0.00000D+00	0.58014D+01	0.20293D+00	0.14696D+02	0.00000D+00	0.00000D+00
14-14	0.53608D+01	0.15122D+02	0.64319D+03	0.00000D+00	0.58014D+01	0.19989D+00	0.14696D+02	0.00000D+00	0.00000D+00

# COMPONENT OUTPUT DATA

COMPONENT NO. TYPE	DATOUT1	DATOUT2	DATOUT3	DATOUT4	DATOUT5	DATOUT6	DATOUT7	DATOUT8	DATOUT9
1 INLET	0.00000D+00	0.00000D+00	0.00000D+00	0.10000D+01	0.10000D+01	0.00000D+00	0.10000D+01	0.10000D+01	0.00000D+00
2 COMPRES	-0.22630D+02	0.10000D+01	0.20000D+01	0.18000D+01	0.35632D+01	0.00000D+00	0.72456D+01	0.85000D+00	0.10500D+01
3 SPLITTER	0.45500D+00	0.00000D+00	0.00000D+00	0.78000D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
4 COMPRES	-0.51091D+03	0.10000D+01	0.00000D+00	0.13000D+01	0.30222D+02	0.10000D+01	0.22851D+01	0.79000D+00	0.99192D+01
5 HEAT EXC	0.20000D-01	0.00000D+00	0.00000D+00	0.40000D+00	0.10000D+01	0.11597D+03	0.19180D+00	-0.11102D-15	0.00000D+00
6 DUCT B	0.00000D+00	0.00000D+00	0.00000D+00	0.36395D-01	0.00000D+00	0.31958D+03	0.00000D+00	0.10000D+01	0.21873D+04
7 TURBINE	0.53354D+03	0.10000D+01	0.10000D+01	0.43000D+01	0.97391D-04	0.50000D+04	0.29869D-01	0.84500D+00	0.39655D+01
8 DUCT B	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
9 TURBINE	0.20000D+03	0.10000D+01	0.10000D+01	0.13676D+02	0.11124D-03	0.50000D+04	0.33623D-01	0.84800D+00	0.18561D+01
10 NOZZLE	0.73340D+02	0.93342D+03	0.11986D+01	0.13676D+02	0.49441D+02	0.10000D+01	0.98500D+00	0.18569D+01	0.11986D+01
12 NOZZLE	0.41209D+02	0.24732D+03	0.10290D+01	0.49441D+02	0.49441D+02	0.10000D+01	0.98500D+00	0.18569D+01	0.10290D+01
13 SHAFT	0.00000D+00	0.10000D+01	0.10000D+01	0.10000D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
14 SHAFT	0.00000D+00	0.10000D+01	0.10000D+01	0.10000D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00
15 LOAD	-0.20000D+03	0.10000D+01	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00	0.00000D+00

MACH= 0.0000 ALTITUDE= 0. RECOVERY= 1.0000 8 ITERATIONS 20 PASSES

AIRFLOW (LB/SEC) 114.55 GROSS THRUST 114.55 FUEL FLOW (LB/HR) 319.58  
 NET THRUST 7.80 TSFC 2.7900 NET THRUST/AIRFLOW 14.6857  
 TOTAL INLET DRAG 0.00 TOTAL BRAKE SHAFT HP 0.00 BOATTAIL DRAG 0.00  
 INSTALLED THRUST 114.55 INSTALLED TSFC 2.7900 SPILLAGE + LIP DRAG 0.00

Figure 6.9 Turbomachinery Output File for Sample Case 2

## 7 Conclusions

The computer program described in this report can simulate both design point and off-design operation of a combined-cycle engine. It retains the flexibility of the two original programs on which it is based. Widely varying engine configurations can be evaluated for their power, performance and efficiency as well as the influence of altitude and air speed. Although the program was developed to simulate aircraft engines, it can be used with equal success for stationary and automotive applications as well.

The program has been tested for a wide variety of engine configurations. A student project is currently underway at Iowa State University to use the program to simulate potential engines for a high-altitude, long-endurance aircraft such as the Boeing Condor [8]. This is the type of application for which the program was intended and it should provide useful information to allow comparisons between engine configurations as well as for optimizing a given engine design.

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## 9 Appendices

### 9.1 Appendix A: Bibliography on Two-Stroke Engine Scavenging

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## 9.2 Appendix B: Second Law Analysis

Second law analysis is a technique for analyzing thermodynamic systems that goes beyond traditional energy balances based on the first law of thermodynamics. Second law analysis uses the second law of thermodynamics to determine the fraction of the energy stored or transported in a process that could be converted to useful work. This type of analysis uses a property called "availability."

Availability is the maximum theoretical work output that could be developed in bringing a system into equilibrium with a reference environment. In general, this involves all work that could be obtained by exploiting differences in velocity, potential energy, temperature, pressure, and chemical potential between the system and the environment. When thermal, mechanical, and chemical equilibria are attained and the system is at rest and zero elevation relative to the reference environment, no further potential exists for developing work. In this condition, the system and environment combination is said to be at the dead state. The value of the availability depends on both the state of the system and the state of the environment; it is a measure of the system's thermodynamic potential relative to the chosen environment [9].

Availability is not a conserved quantity. It can be destroyed by irreversibilities within the system such as friction, heat transfer, mixing, turbulence, etc. However, it is possible to combine these terms into a single loss term and write an availability balance for a system that is analogous to the energy equation.

$$\underbrace{\frac{dA}{d\theta}}_1 = \underbrace{\{q'(1 - T^0/T)dA\}}_2 - \underbrace{\left(W' - p^0 \frac{dV}{d\theta}\right)}_3 + \underbrace{\frac{m'_f}{M_f} \dot{a}_{f,flow}}_4 - \underbrace{I'}_5 \quad (9.1)$$

The numbered terms in this equation can be interpreted as availability quantities as follows:

- Term 1: the rate of change of availability in the control volume
- Term 2: the rate of availability transfer associated with heat transfer from the gases to the wall
- Term 3: net rate of availability transfer to the piston associated with work
- Term 4: rate of availability input to the control volume with the fuel, including the availability input associated with flow work
- Term 5: rate of availability destruction due to irreversibilities within the control volume

Second law analysis consists of applying the availability balance to the components of a system to determine whether the processes in that component are destroying availability. This allows the individual processes within a system that responsible for inefficiency to be identified.

## Computer Program ACV

A computer program, called ACV, has been written that performs a second law analysis of a combined cycle engine. The program is interactive, and the user enters information such as temperature, pressure, mass flow rate, etc., from the output files of the cycle simulation program, CCE. The output is given in terms of the availability transferred due to heat transfer, work, and mass flows as well as the availability destroyed by irreversibilities.

A sample output from the program is shown in Figure 9.1. This case corresponds to the V-6 engine sample case discussed in Section 6.1. The results can be summarized as:

Availability input with air	1.68
Availability input with fuel	1796.26
Total availability added: 1797.94 Btu/sec	
Work	711.54
Heat	87.89
Irreversibilites	637.34
Availability exiting with exhaust	342.74
Availability exiting with air	18.63
Total availability accounted for: 1798.14 Btu/sec	

These results show that of the availability added to the combined-cycle engine,  $711.54/1797.94 = 39.6\%$  is converted to work. This compares to a first law brake thermal efficiency of 44.0% based on the lower heating value of the fuel. The analysis also shows that the most significant loss is the irreversibility of the combustion process. 27.6% of the availability is destroyed by the irreversible combustion process, 3.6% is destroyed in the heat exchanger and 19.1% exits with the exhaust gases.

SECOND LAW ANALYSIS: SUMMARY OF RESULTS  
 UNITS = BTU/SEC

DEVICE NO.	DEVICE TYPE	AIN	AOUT	WORK	AQ	IRREV
1	1	1.68	1.68	0.00	0.00	0.00
2	4	1.68	15.43	-16.00	0.00	2.25
3	7	15.43	15.43	0.00	0.00	0.00
4	4	4.83	332.39	-361.18	0.00	33.62
5	6	343.00	278.40	0.00	0.00	64.59
6	10	2055.95	901.67	570.15	-87.89	496.24
7	5	901.95	495.62	377.18	0.00	29.15
8	2	495.62	495.62	0.00	0.00	0.00
9	5	495.62	342.74	141.39	0.00	11.43
10	9	342.74	342.74	0.00	0.00	0.00
11	9	18.63	18.63	0.00	0.00	0.00
TOTAL			711.54	-87.89		637.34

TOTAL AVAILABILITY ADDED WITH FUEL: 1796.26

Figure 9.1 Sample Output from Second Law Analysis Program ACV

### 9.3 Appendix C: Use of Centrifugal Compressor Data in the Combined-Cycle Engine Simulation

The computer program NNEPEQ is accompanied by a set of default compressor and turbine maps that are scaled from a 100 lb/sec axial-flow compressor and turbine. Since a 1000 hp combined-cycle engine such as that discussed in Section 6.1 is likely to use a 2 lb/sec centrifugal compressor, the effect of using actual data for a compressor of this type was investigated. Skoch and Moore [10] collected experimental data on the performance of two 10 lb/sec centrifugal compressors. The blade thickness of one of the compressors was increased to simulate a scaled-up 2 lb/sec centrifugal compressor. While the performance data for the simulated 2 lb/sec compressor would have been ideal, only data for the thin-blade compressor were available. These data were used to create the compressor map shown in Figure 9.2. When this map was used for the high pressure compressor in a sample case of a combined-cycle engine, the results shown in Table 9.1 were obtained.

Table 9.1 Comparison of Default Compressor Map and 10 lb/sec Centrifugal Compressor Map

Turbine Inlet Temperature (deg R)	Default Compressor					Centrifugal Compressor				
	HP	Surge	Mar	Effic	PR	HP	Surge	Mar	Effic	PR
2300	454	30.2		78.9	10.1	455	49.1		79.0	10.1
2200	417	34.4		80.4	9.6	394	51.9		78.0	9.1
2100	377	37.1		81.6	8.9	344	54.9		77.9	8.3
2000	335	38.3		82.5	8.3	284	57.6		76.7	7.2
1900	286	37.2		82.6	7.4	232	59.7		76.0	6.3
1800	224	33.9		80.6	6.2	187	61.9		75.8	5.4
1700	170	31.6		79.0	5.2	134	63.3		74.6	4.4
1600	123	25.6		78.0	4.2	88	63.2		74.0	3.5
1500	78	9.1		77.0	3.3	56	60.6		75.7	2.8

As is clear from the table, the centrifugal compressor maintained a wider surge margin and higher efficiency than the default compressor. The pressure rise through the centrifugal compressor dropped off somewhat faster as the turbine inlet temperature was decreased. Although not shown, a second series of cases was also run with the "R" value of the centrifugal compressor adjusted so that the initial surge margin of the default compressor and the centrifugal compressor matched. In this case, the relationship between the turbine inlet temperature and the compressor pressure ratio and efficiency was altered somewhat but the performance was still below the default compressor.

This study makes it clear that while the default maps can be used for comparisons between configurations, actual maps are required to obtain accurate performance predictions. The default maps were used for the sample cases discussed in Section 6.0.

10 LB/SEC CENTRIFUGAL COMPRESSOR									
1101	1	0.00	70.0	80.0	90.0	100.0	1.500	1.600	
ANGL	5	60.0	1.100	1.200	1.300	1.400	4.02	4.03	
SPED	7	1.000	3.10	3.42	3.72	3.95	5.10	5.11	
R	7	2.81	4.10	4.49	4.87	5.09	6.54	6.55	
FLOW	7	3.71	5.43	5.96	6.42	6.53	8.26	8.27	
FLOW	7	4.90	7.44	8.06	8.24	8.25	11.03	11.04	
FLOW	7	6.68	9.95	10.99	11.01	11.02			
FLOW	7	9.37							
EOT									
10 LB/SEC CENTRIFUGAL COMPRESSOR									
1102	1	0.00	70.0	80.0	90.0	100.0	1.500	1.600	
ANGL	5	60.0	1.100	1.200	1.300	1.400	0.640	0.580	
SPED	7	1.000	0.745	0.750	0.751	0.724	0.652	0.600	
R	7	0.740	0.754	0.760	0.765	0.720	0.670	0.620	
EFF	7	0.750	0.780	0.782	0.779	0.730	0.660	0.595	
EFF	7	0.770	0.790	0.797	0.735	0.718	0.660	0.595	
EFF	7	0.789	0.793	0.773	0.729	0.709	0.692	0.675	
EFF	7	0.784							
EOT									
10 LB/SEC CENTRIFUGAL COMPRESSOR									
1103	1	0.00	70.0	80.0	90.0	100.0	1.500	1.600	
ANGL	5	60.0	1.100	1.200	1.300	1.400	2.03	1.81	
SPED	7	1.000	2.39	2.38	2.33	2.23	2.57	2.29	
R	7	2.39	3.15	3.12	3.05	2.88	3.30	2.93	
PR	7	3.15	4.15	4.15	4.02	3.68	4.16	3.70	
PR	7	4.15	5.68	5.56	5.15	4.64	5.14	4.58	
PR	7	5.68	7.58	7.05	6.36	5.74			
PR	7	7.96							
EOT									

Figure 9.2 Centrifugal Compressor Map

#### 9.4 Appendix D: Subroutine for Simulating Opposed Piston Engines with Crankshafts Out-of-Phase

A FORTRAN subroutine was developed for use with opposed piston engines with out-of-phase crankshafts. The subroutine has been tested but was not incorporated into the CCE simulation program. Since this type of engine is very specialized, the added difficulty to the program user of having to input additional engine specifications was considered undesirable. The subroutine could be added with only minimal program modifications. The volume subroutine listing, along with a simple test program, is provided in Figure 9.3.

```

C
C   THIS IS A PROGRAM TO TEST THE VOLUME SUBROUTINE FOR AN OPPOSED
C   PISTON ENGINE WITH CRANKSHAFTS OUT-OF-PHASE
C
C       COMMON/ENGINE/ CONROD,BORE,STROKE,CR,VCL,MODE,NCYCLE,LTYPE
C       COMMON/OPPSD/ PSI
C   SPECIFY VALUES OF INPUT VARIABLES
C       CONROD=9.
C       BORE=4.5
C       STROKE=4.5
C       CR=16.
C       MODE=1
C       PSI=10.
C   CALCULATE CLEARANCE VOLUME (REQUIRED BEFORE FIRST CALL TO
C   VOLUME SUBROUTINE)
C       CALL CLEAR
C       WRITE(5,*) 'VCL = ',VCL
C       DO 20 I=1,21
C           CA=-10.+FLOAT(I-1)
C           CALL VOL2(CA,V,DVCA)
C       WRITE(6,*) CA,V,DVCA
20  CONTINUE
C       STOP
C       END
C
C   SUBROUTINE VOL2(CA,V,DVCA)
C   COMMON/ENGINE/ CONROD,BORE,STROKE,CR,D,VCL,MODE,NCYCLE,LTYPE
C   COMMON/OPPSD/ PSI
C
C   CALCULATE CYLINDER VOLUME AND VOLUME DERIVATIVE
C
C       DUMMY1=SQRT(CONROD**2-(STROKE/2.*SIN(CA/57.29578))**2)
C       DUMMY2=SQRT(CONROD**2-(STROKE/2.*SIN((CA+PSI)/57.29578))**2)
C       XL=STROKE/2.*(1.-COS(CA/57.29578))+CONROD-DUMMY1
C       XR=STROKE/2.*(1.-COS((CA+PSI)/57.29578))+CONROD-DUMMY2
C       V=VCL+0.7853982*BORE*BORE*(XL+XR)
C       DXLDT=STROKE/2.*SIN(CA/57.29578)*
1       (1.+STROKE/2.*COS(CA/57.29578)/DUMMY1)
C       DXRDT=STROKE/2.*SIN((CA+PSI)/57.29578)*
1       (1.+STROKE/2.*COS((CA+PSI)/57.29578)/DUMMY2)
C       DVCA=0.7853982*BORE*BORE*(DXLDT+DXRDT)/57.29578
C       RETURN
C       END
C
C   SUBROUTINE CLEAR
C   COMMON/ENGINE/ CONROD,BORE,STROKE,CR,VCL,MODE,NCYCLE,LTYPE
C   COMMON/OPPSD/ PSI
C
C   CALCULATE CYLINDER CLEARANCE VOLUME
C
C       CA=-PSI/2.
C       DUMMY1=SQRT(CONROD**2-(STROKE/2.*SIN(CA/57.29578))**2)
C       DUMMY2=SQRT(CONROD**2-(STROKE/2.*SIN((CA+PSI)/57.29578))**2)
C       XL=STROKE/2.*(1.-COS(CA/57.29578))+CONROD-DUMMY1
C       XR=STROKE/2.*(1.-COS((CA+PSI)/57.29578))+CONROD-DUMMY2
C       VMIN=0.7853982*BORE*BORE*(XL+XR)
C       CA=CA+180.
C       DUMMY1=SQRT(CONROD**2-(STROKE/2.*SIN(CA/57.29578))**2)
C       DUMMY2=SQRT(CONROD**2-(STROKE/2.*SIN((CA+PSI)/57.29578))**2)
C       XL=STROKE/2.*(1.-COS(CA/57.29578))+CONROD-DUMMY1
C       XR=STROKE/2.*(1.-COS((CA+PSI)/57.29578))+CONROD-DUMMY2
C       VMAX=0.7853982*BORE*BORE*(XL+XR)
C       VCL=(VMAX-CR*VMIN)/(CR-1.)
C       RETURN
C       END

```

Figure 9.3 Cylinder Volume Subroutine for an Opposed Piston Engine with Out-of-Phase Crankshafts